RADIATION DOSIMETRY

During the early days of radiological experience, there was no precise unit of radiation dose that was suitable either for radiation protection or for radiation therapy. For purposes of radiation protection, a common “dosimeter” used was a piece of dental film with a paper clip attached. A daily exposure great enough just to produce a detectable shadow, called a “paper-clip” unit, was considered a maximum permissible dose.

For greater doses and for therapy purposes, the dose unit was frequently the “skin erythema unit.” Because of the great energy dependence of these dose units as well as other inherent shortcomings, neither of these two units could be biologically meaningful or useful either in the quantitative study of the biological effects of radiation or for radiation safety purposes. Furthermore, since the fraction of the energy in a radiation field that is absorbed by the body is energy dependent, it is necessary to distinguish between *exposure and absorbed doses.*

Absorbed Dose (Gray)

Radiation damage depends on the absorption of energy from the radiation and is approximately proportional to the mean concentration of absorbed energy in irradiated tissue. For this reason, the basic unit of radiation dose is expressed in terms of absorbed energy per unit mass of tissue, that is, radiation absorbed dose =

$$\text{radiation absorbed dose} = \frac{\Delta E}{\Delta m}. \qquad (5\text{-}1)$$

The unit for radiation absorbed dose in the SI system is called the *gray (Gy) and is* defined as One *gray is an absorbed radiation dose of one joule per kilogram.*

$$1\,\mathrm{Gy} = 1\,\frac{\mathrm{J}}{\mathrm{kg}}. \qquad (5\text{-}2)$$

The gray is universally applicable to all types of ionizing radiation dosimetry—irradiation due to external fields of γ rays, n, or charged particles as well as that due to internally deposited radionuclides.

rad (Radiation Absorbed Dose)

Before the introduction of the SI units, radiation dose was measured by a unit called the rad.

One *rad is defined as an absorbed radiation dose of 100* ergs /g

$$1\ \text{rad} = 100\ \frac{\text{ergs}}{\text{g}}.$$

Since $1\ \text{J} = 10^7$ ergs, and since $1\ \text{kg} = 1000$ g,

$$1\ \text{Gy} = 100\ \text{rads}. \qquad (5\text{-}3)$$

$$1\ \text{rad} = 0.01\ \text{Gy} = 1\ \text{centigray (cGy)}.$$

The radiation absorbed dose concept implies that the absorbed energy is uniformly distributed throughout the entire mass of the tissue of interest. On the cellular and subcellular levels that are of interest to molecular biologists, the biological effects are proportional to the number and types of intramolecular bonds that are broken rather than to the concentration of absorbed energy within the cell. On the tissue level, the number of such intramolecular breaks in the tissue is proportional to the radiation absorbed dose. The distinction between microdosimetry and radiation absorbed dose may be illustrated with the following thought experiment.

Example 5.1

Consider a single cell, with dimensions $10\ \mu m \times 10\ \mu m \times 10\ \mu m$ *and mass* $= 10^{-12}$ kg, in a tissue of weight 0.1 g, in which a low LET particle, 1 keV/μm, *transfers* 1 keV to the cell as it passes through the cell. Calculate the radiation absorbed dose to the tissue.

Solution

The radiation absorbed dose to the tissue is calculated as

$$\text{radiation absorbed dose (tissue)} = \frac{10\,\text{keV} \times 1.6 \times 10^{-16}\,\dfrac{\text{J}}{\text{keV}} \times 1\,\dfrac{\text{Gy}}{\text{J/kg}}}{1 \times 10^{-4}\,\text{kg}}$$

$$= 1.6 \times 10^{-11}\,\text{Gy},$$

which is an infinitesimally small dose. However, if the absorbed dose were to be(erroneously) applied to the single cell, the calculated dose would be

$$\text{radiation absorbed dose (cell)} = \frac{10\,\text{keV} \times 1.6 \times 10^{-16}\,\dfrac{\text{J}}{\text{keV}} \times 1\,\text{Gy} \cdot \text{kg/J}}{1 \times 10^{-12}\,\text{kg}}$$

$$= 1.6 \times 10^{-3}\,\text{Gy}.$$

EXTERNAL EXPOSURE

X- and Gamma Radiation

Exposure Unit

For external radiation of any given energy flux, the absorbed dose to any region within an organism depends on the type and energy of the radiation, the depth within the organism at the point at which the absorbed dose is required, and elementary constitution of the absorbing medium at this point.

For example, bone, consisting of higher-atomic-numbered elements (Ca and P) than soft tissue (C, O, H, and N), absorbs more energy from an X-ray beam per unit mass of absorber than soft tissue. For this reason, the X-ray fields to which an organism may be exposed are frequently specified in *exposure units*. ***The exposure unit*** *is a radiometric unit rather* than a dosimetric unit. That is, it is a measure of the photon fluence and is related to the amount of energy transferred from the X-ray field to a unit mass of *air*.

If the amount of exposure, measured in exposure units, is known, then knowing the energy of the X-rays and the composition of the irradiated medium, one can calculate the absorbed dose to any part of the irradiated medium. One exposure unit is defined as that quantity of X- or gamma radiation that produces, in air, ions carrying one coulomb of charge (of either sign) per kilogram of air. It does not have a special name, and is being called an "X unit".

$$1 \text{ X unit} = 1 \text{ C/kg air.} \tag{5-4}$$

The exposure unit is based on ionization of air because of the relative ease with which radiation induced ionization can be measured. At quantum energies less than several KeV and more than several MeV, it becomes difficult to fulfill the requirements for measuring the exposure unit. Accordingly, the use of the exposure unit is limited to X- or γ rays whose quantum energies do not exceed 3 MeV.

For higher energy photons, exposure is expressed in units of watt-seconds per square meter and exposure rate is expressed in units of watts per square meter. The operational definition of the exposure unit may be converted into the more fundamental units of energy absorption per unit mass of air by using the fact that the charge on a single ion is 1.6×10^{-19} C and that the average energy dissipated in the production of a single ion pair in air is 34 eV. Therefore,

$$1\ \text{X unit} = 1\frac{\text{C}}{\text{kg}}\text{air} \times \frac{1\ \text{ion}}{1.6 \times 10^{-19}\ \text{C}} \times 34\frac{\text{eV}}{\text{ion}} \times 1.6 \times 10^{-19}\frac{\text{J}}{\text{eV}} \times 1\frac{\text{Gy}}{\text{J/kg}} = 34\,\text{Gy (in air)}. \tag{5-5}$$

It should be noted that the exposure unit is an integrated measure of exposure and is independent of the time over which the exposure occurs. The strength of an X-ray or gamma-ray field is usually expressed as an exposure rate, such as coulombs per kilogram per hour. The total exposure, of course, is the product of exposure rate and time.

Roentgen

Formerly, before the SI system was introduced, the unit of X-ray exposure was called the *roentgen and was symbolized by R. The roentgen was defined as that* quantity of X-or γ radiation that produces ions carrying one statcoulomb (sC)(1 sC = 3×10^9 C) of charge of either sign per cm^3 of dry air at 0°C and 760 mm Hg:

$$1\,R = 1\,sC/cm^3. \qquad \textbf{(5-6)}$$

Since 1 ion carries a charge of 4.8×10^{-10} sC and the mass of 1 cm^3 of standard air is 0.001293 g, one can calculate the dose to the air from an exposure of 1 R:

$$1\ \mathrm{R} = 1\ \mathrm{sC/cm^3\ air} \times \frac{1\ \mathrm{cm^3\ air}}{1.29 \times 10^{-3}\ \mathrm{g/cm^3\ air}} \times \frac{1\ \mathrm{ion}}{4.8 \times 10^{-10}\ \mathrm{sC}} \times 34\frac{\mathrm{eV}}{\mathrm{ion}}$$

$$\times 1.6 \times 10^{-12}\frac{\mathrm{erg}}{\mathrm{eV}} \times \frac{1\ \mathrm{rad}}{100\frac{\mathrm{erg}}{\mathrm{g}}}$$

$$1\ \mathrm{R} = 0.877\ \mathrm{rad\ (to\ air)}.$$

When exposure is measured in roentgens, X-ray or γ ray field strength is measured in units such as roentgens per minute or milliroentgens per hour. (A,"mR," is equal to 0.001 R.)

The relationship between the coulomb per kilogram exposure unit and the roentgen may be calculated as follows:

$$\frac{34\,\dfrac{\text{J/kg}}{\text{C/kg}} \times 10^{7}\,\dfrac{\text{ergs}}{\text{J}} \times \dfrac{1\text{ kg}}{1000\text{ g}}}{87.7\,\dfrac{\text{ergs/g}}{\text{R}}} = 3881\,\frac{\text{R}}{\text{C/kg}}$$

or

$$1\text{ X unit} = 3881\text{ R}. \qquad \textbf{(5-7a)}$$

$$1\text{ R} = (1/3881)\text{X unit} = 2.58 \times 10^{-4}\text{ X unit}. \qquad \textbf{(5-7b)}$$

Example 5.2

Health physics measurements of X-ray and γ ray fields are usually made in units of milliroentgen per hour. If a health physicist finds a γ ray field of 1 mR/h, what is the corresponding exposure expressed in SI units?

Solution

According to Eq. (5-7b),

$$1\,\frac{\mathrm{mR}}{\mathrm{h}} \times 10^{-3}\,\frac{\mathrm{R}}{\mathrm{mR}} = 2.58 \times 10^{-4} \times 10^{-3}\,\frac{\mathrm{C}}{\mathrm{kg}}$$

$$1\ \mathrm{mR/h} = 2.58 \times 10^{-7}\,\frac{\mathrm{C}}{\mathrm{kg}} = 0.258\,\frac{\mu\mathrm{C}}{\mathrm{h}}.$$

Exposure Measurement: The Free Air Chamber

The operational definition of the exposure unit can be satisfied by the instrument shown in Fig.5-1. The X-ray beam enters through the portal and interacts with the cylindrical column of air defined by the entry port diaphragm. All the ions resulting from interactions between the X-rays and the volume of air (A–B–C–D), which is determined by the intersection of the X-ray beam with the electric lines of force from the edges of the collector plate C, is collected by the plates, causing current to flow in the external circuit.

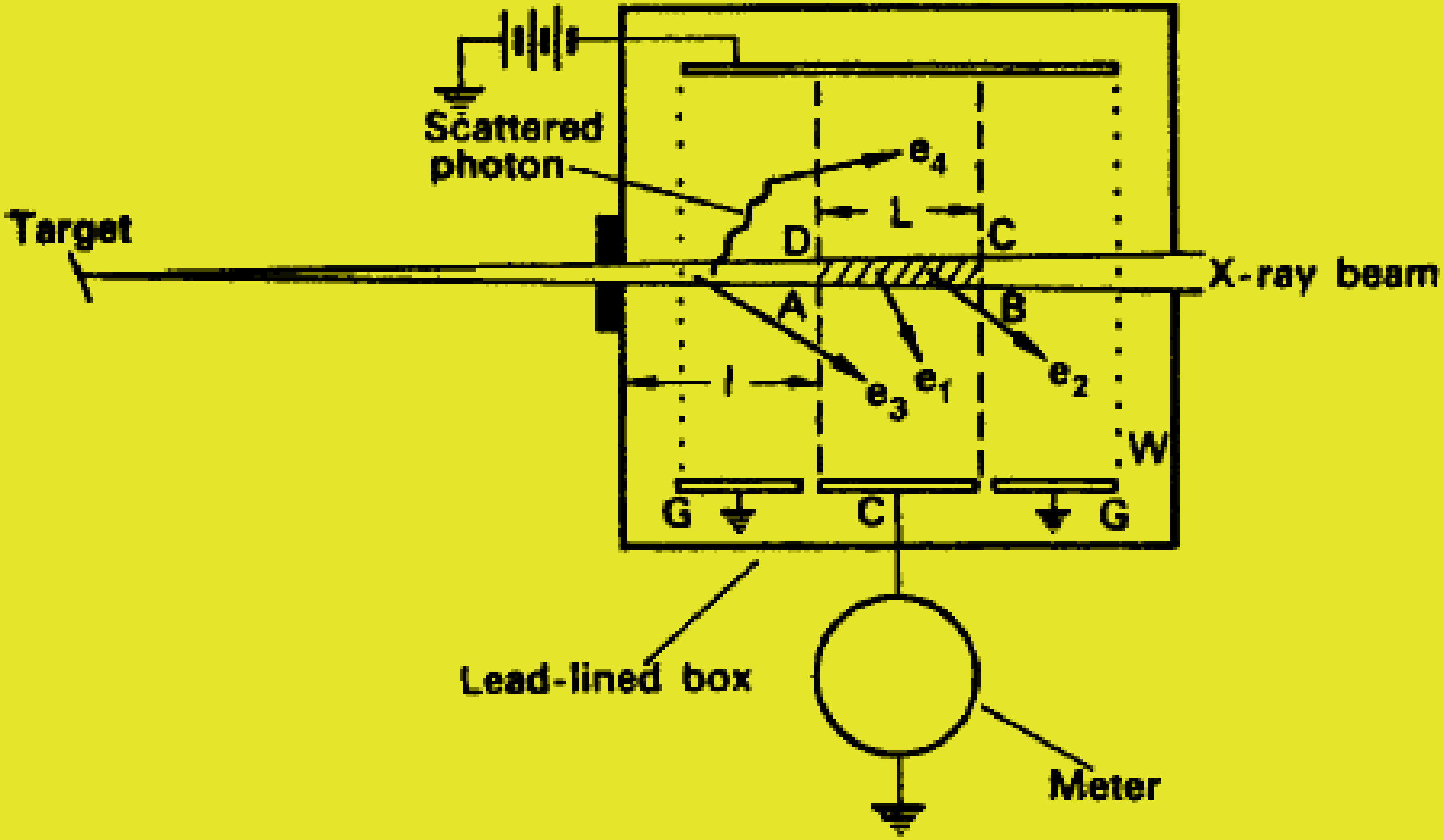


Figure 5-1. Schematic diagram of a parallel-plate ionization chamber.

Most of these collected ions are those produced as the primary ionizing particles lose their energy by ionizing interactions as they pass through the air. (The primary ionizing particles are the Compton es and the photo es resulting from the interaction of the x-rays (photons) with the air.) The guard ring G and the guard wires W help to keep these electric field (E) lines straight and perpendicular to the plates.

The E intensity between the plates is on the order of 100 V/cm high enough to collect the ions before they recombine but not great enough to accelerate the secondary electrons produced by the primary ionizing particles to ionizing energy. The guard wires are connected to a voltage-dividing network to ensure a uniform potential drop across the plates. The number of ions collected because of X-ray interactions in the collecting volume is calculated from the current flow and the exposure rate, in R per h, is then computed.

For the exposure unit to be measured in this way, all the energy of the primary es must be dissipated in the air within the meter. This condition can be satisfied by making the air chamber larger than the max range of the primary es.(For 300-keV X-rays, the spacing between the collector plates is ~ 30 cm and the overall box is a cube of about 50-cm edge.)

The fact that many of the ions produced as a consequence of X-ray interactions within the sensitive volume are not collected is of no significance if as many electrons from interactions elsewhere in the X-ray beam enter the sensitive volume as leave it. This condition is known as electronic equilibrium. When electronic equilibrium is attained, an electron of equal energy enters into the sensitive volume for every electron that leaves.

A sufficient thickness of air, dimension l in Figure 5-1, must be allowed between the beam entrance port and the sensitive volume in order to attain electronic equilibrium For highly filtered 250-kV X-rays, 9 cm of air is required; for 500-kV X-rays, the air thickness required for electronic equilibrium in the sensitive volume increases to 40 cm.

Under conditions of electronic equilibrium and assuming negligible attenuation of the X-ray beam by the air in length l, the ions collected from the sensitive volume result from primary photon interactions at the beam entrance port; the measured exposure, consequently, is at that point and not in the sensitive volume. Free air chambers are in use that measure the quantity of X-rays whose quantum energies reach as high as 500 keV. Higher energy radiation necessitates free air chambers of much greater size.

The technical problems arising from the use of such large chambers make it impractical to use the free air ionization chamber as a primary measuring device for quantum energies in excess of 500 keV. These problems include recombination of ions in the large chamber before they can be collected and secondary ionization due to acceleration of the initial ions by the great potential difference required for large chambers. The use of the free air ionization chamber to measure X-ray exposure rate in C Kg^{-1} S^{-1} is illustrated example 5-3:

Example 5.3

The opening of the diaphragm in the entrance port of a free air ionization chamber is 1 cm in diameter, and the length AB of the sensitive volume is 5 cm. A 200-kV X-ray beam projected into the chamber produces a steady current in the external circuit of 0.01 μA. The temp. at the time of the measurement was 20°C and the pressure was 750 mm Hg. What is the exposure rate in this beam of X-rays?

Solution

A current of 0.01 μA corresponds to a flow of electrical charge of 10^{-8} C/s. The sensitive volume in this case, π × (0.5 cm)^2× 5 cm= 3.927 cm ^{3}. When the pressure and temperature are corrected to standard conditions,

$$\dot{X} = \frac{10^{-8}\ \mathrm{C/s}}{3.927\ \mathrm{cm}^3 \times 1.293 \times 10^{-6}\dfrac{\mathrm{kg}}{\mathrm{cm}^3}} \times \frac{293}{273} \times \frac{760}{750}$$

$$= 2.14 \times 10^{-3}\frac{\mathrm{C/kg}}{\mathrm{s}}.$$

In the traditional system of units, this exposure rate corresponds to

$$2.14 \times 10^{-3}\frac{\mathrm{C/kg}}{\mathrm{s}} \times 3.881 \times 10^{3}\ \frac{\mathrm{R}}{\mathrm{C/kg}} = 8.31\frac{\mathrm{R}}{\mathrm{s}}.$$

Exposure Measurement: The Air Wall Chamber

The free air ionization chamber described above is practical only as a primary laboratory standard. For field use, a more portable instrument is required. Such an instrument could be made by compressing the air around the measuring cavity. If this were done, then the conditions for defining the exposure unit would continue to be met. In practice, of course, it is difficult to construct an instrument whose walls were made of compressed air.

However, it is possible to make an instrument with walls of "air-equivalent" material—that is, a wall material whose X-ray absorption properties are very similar to those of air. Such a chamber can be built in the form of an electrical capacitor; its principle of operation can be explained with the aid of Figure 5-2. The instrument consists of an outer cylindrical wall, about 4.75-mm thick, made of electrically conducting plastic. Coaxial with the outer wall, but separated from it by a very high-quality insulator, is a center wire.

This center wire, or central anode, is positively charged with respect to the wall. When the chamber is exposed to X-radiation or to gamma radiation, the ionization, which is produced in the measuring cavity as a result of interactions between photons and the wall, discharges the condenser, thereby decreasing the potential of the anode.

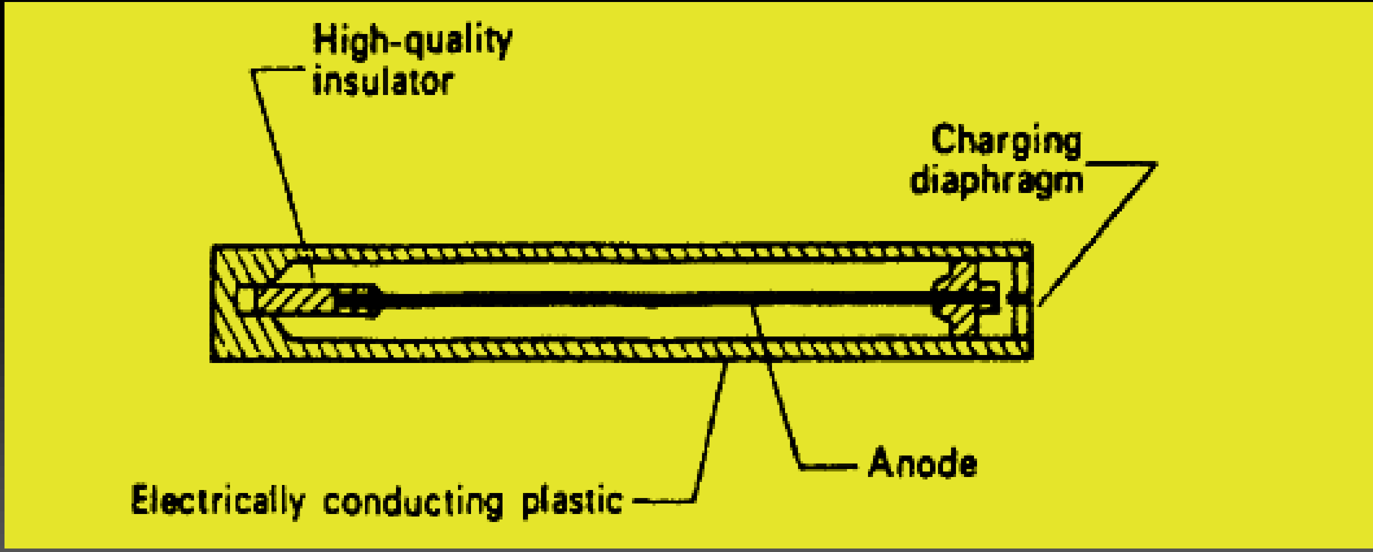


Fig 5-2. condenser-type pocket ionization chamber.

This decrease in the anode voltage is directly proportional to the ionization produced in the cavity, which in turn is directly proportional to the radiation exposure.

Example 5.4

Given chamber volume = 2 cm3,
chamber is filled with air at STP,
capacitance = 5 pF,
voltage across chamber before exposure to radiation = 180 V,
voltage across chamber after exposure to radiation = 160 V,
and exposure time = 0.5 h.
Calculate the radiation exposure and the exposure rate.

Solution

The exposure is calculated as follows:

$$C \times \Delta V = \Delta Q \qquad \textbf{(5.8)}$$

where

C = capacitance, farads
V = potential, volts
Q = charge, coulombs

$$5 \times 10^{-12}\,\mathrm{F} \times (180 - 160)\,\mathrm{V} = 1 \times 10^{-10}\,\mathrm{C}.$$

Since one exposure unit is equal to 1 C/kg, the exposure measured by this chamber is

$$\frac{1 \times 10^{-10}\,\mathrm{C}}{2\,\mathrm{cm}^3 \times 1.293 \times 10^{-6}\dfrac{\mathrm{kg}}{\mathrm{cm}^3}} = 3.867 \times 10^{-5}\,\frac{\mathrm{C}}{\mathrm{kg}},$$

which corresponds to

$$3.867 \times 10^{-5}\,\frac{\mathrm{C}}{\mathrm{kg}} \times 3881\,\frac{\mathrm{R}}{\mathrm{C/kg}} = 0.150\,\mathrm{R} = 150\,\mathrm{mR},$$

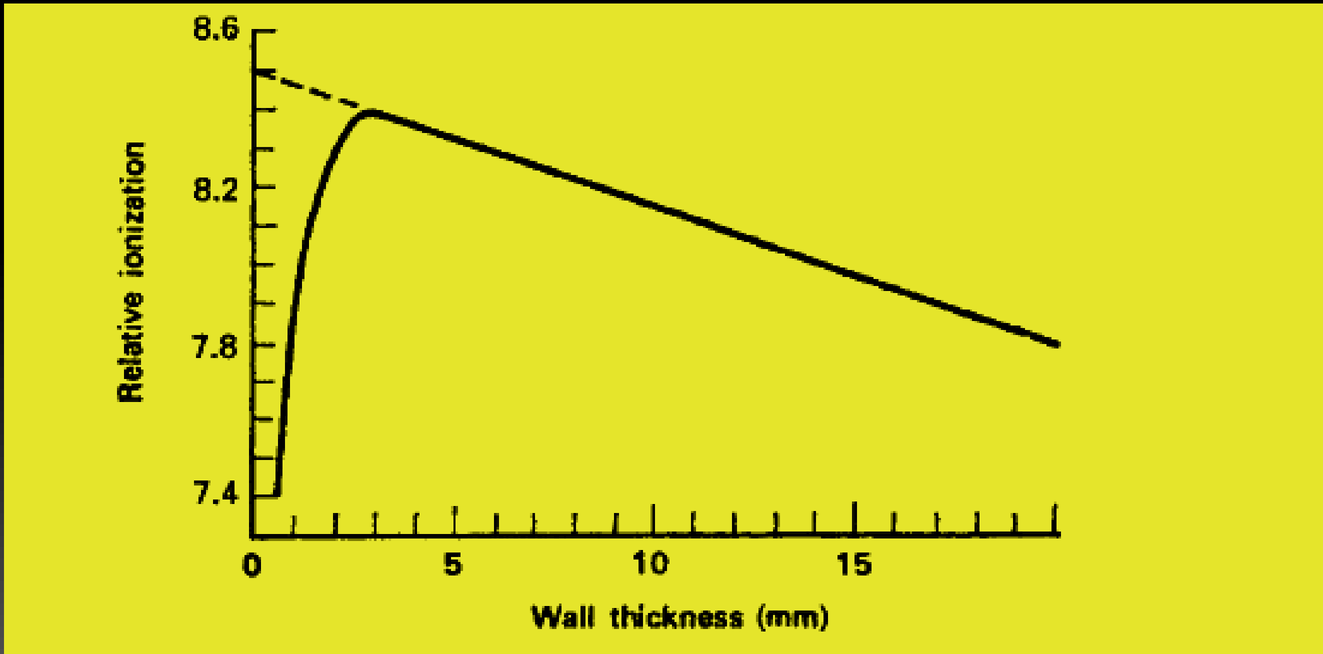
and the exposure rate was

$$\frac{3.867 \times 10^{-5}\,\mathrm{C/kg}}{0.5\,\mathrm{h}} = 77.3 \times 10^{-6}\,\frac{\mathrm{C/kg}}{\mathrm{h}} = 77.3\,\frac{\mu\mathrm{C/kg}}{\mathrm{h}}$$

or $300\,\dfrac{\mathrm{mR}}{\mathrm{h}}$.

A chamber built according to this principle is called an “air wall” chamber. When such a chamber is used, care must be taken that the walls are of the proper thickness for the energy of the radiation being measured. If the walls are too thin, an insufficient number of photons will interact to produce primary electrons; if they are too thick, the primary radiation will be absorbed to a significant degree by the wall and an attenuated primary-electron fluence will result.

The determination of the optimum thickness may be illustrated by an experiment in which the ionization produced in the cavity of an ionization chamber is measured as the wall thickness is increased from a very thin wall until it becomes relatively thick. When this is done and the cavity ionization is plotted vs the wall thickness, (see Figure 5-3).



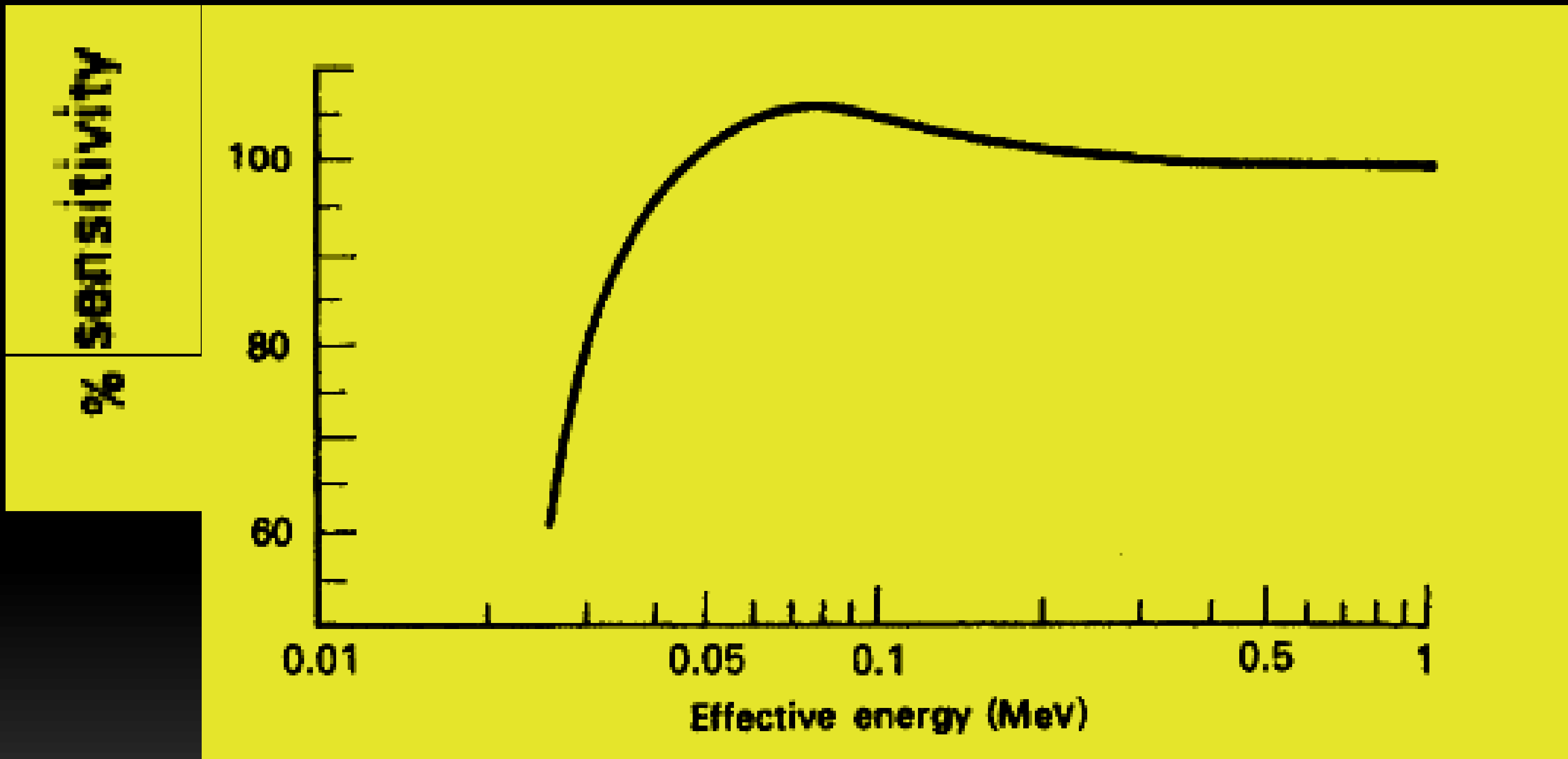
Since the cavity ionization is caused mainly by primary es resulting from photon (γ-ray) interactions with the wall, increasing the wall thickness allows more photons to interact, thereby producing more primary es, which ionize the gas in the chamber as they traverse the cavity. However, when the wall thickness reaches a point where a primary e produced at the outer surface of the wall is not sufficiently energetic to pass through the wall into the cavity, the ionization in the cavity begins to decrease. The wall thickness at which this just begins is the equilibrium wall thickness.

As the wall material departs from air equivalence, the response of the ionization chamber becomes energy dependent. By proper choice of wall material and thickness, the max. in the curve of Fig 5-3 can be made broad, and the ionization chamber, as a consequence, can be made relatively energy independent over a wide range of quantum energies. In practice, this approximately flat response spans the energy range from about 200 keV to about 2 MeV (in this range of Compton effect is the predominant mechanism of energy transfer).

For lower energies, the probability of a Compton interaction increases approximately in direct proportion to the wavelength, while the probability of a photoelectric interaction is approximately proportional to the cube of the photon's wavelength. The total number of primary electrons increases and therefore the sensitivity of the chamber also increases; the increased sensitivity, however, reaches a peak as the quantum energy decreases and then, because of the severe attenuation of the incident radiation by the chamber wall, the sensitivity rapidly decreases.

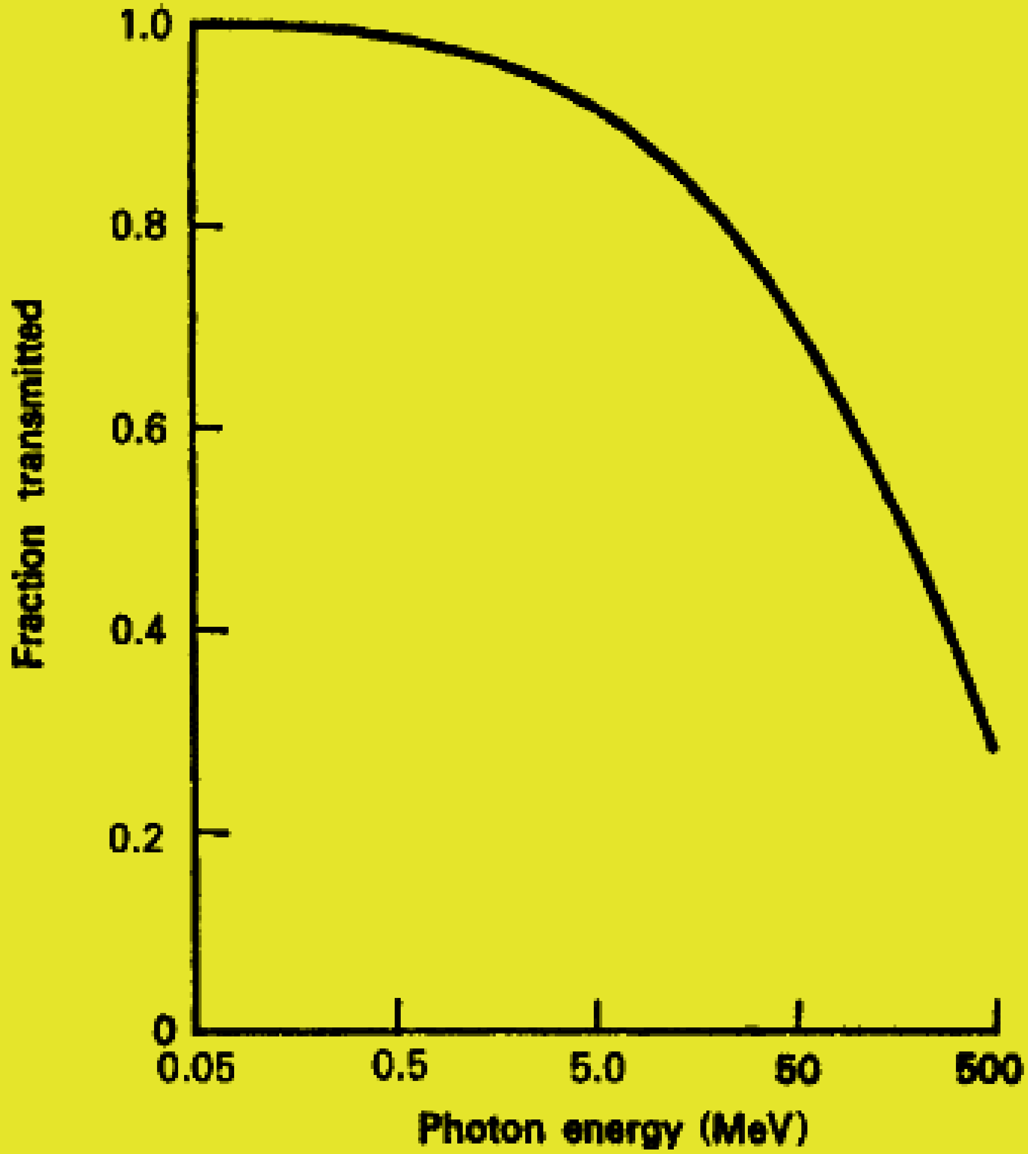
These effects are shown in Figure 5-4, a curve showing the energy correction factor for a pocket dosimeter. For quantum energies greater than 3 MeV, neither coulombs per kilogram nor roentgen is used as the unit of measurement of exposure. This is due to the fact that the high energy and consequently the long range of the primary electrons produced in the wall, makes it impossible to build an instrument that meets the criteria for measuring the exposure. Because of the long range of the primary electrons ,very thick walls are necessary.

Figure 5-4. Energy dependence characteristics of the pocket dosimeter.



However, when the walls are sufficiently thick, on the basis of the range of the primary electrons, they attenuate the photons (gamma radiation) to a significant degree, as shown in Figure 5-5. Under these conditions, it is not possible to attain electronic equilibrium since the radiation intensity within the wall is not constant and the primary electrons, consequently, are not produced uniformly throughout the entire volume of wall from which they may reach the cavity.

Figure 6-5. Fractional number of photons transmitted through an air wall of thickness equal to the max. range of the secondaryes.



Exposure–Dose Relationship

The air-wall chamber, as the name implies, measures the energy absorption in air. In most instances, we are interested in the energy absorbed in tissue. Since energy absorption is approximately proportional to the electronic density of the absorber in the energy region where exposure units are valid, it can be shown that the tissue dose is not necessarily equal to the air dose for any given radiation field.

For example, if we consider muscle tissue to have a specific gravity of 1 and to have an elementary composition of 5.98 $\times 10^{22}$ H atoms per gram, 2.75 $\times 10^{22}$ O atoms per gram, 0.172$\times 10^{22}$ N atoms per gram, and 6.02$\times 10^{21}$ C atoms per gram, then the electronic density is 3.28 $\times 10^{23}$ e per gram. For air, whose density is1.293$\times 10^{-3}$ g/cm3, the electronic density is 3.01$\times 10^{23}$ e/gram. The energy absorption, in J/Kg of tissue, corresponding to an exposure of 1 C/kg air is, therefore.

$$\frac{3.28}{3.01} \times 34 \frac{\mathrm{J}}{\mathrm{kg}} \text{ air} = 37 \frac{\mathrm{J}}{\mathrm{kg}} \text{ tissue.}$$

This value agrees very well with calorimetric measurements of energy absorption by soft tissue from an exposure of 1 C/kg air. By analogy, an exposure of 1 R, corresponds to 87.7 ergs/g of air, leads to an absorption of 95 ergs/g muscle tissue. This tissue dose from a 1-R exposure is very close to the tissue dose of 100 ergs/g, which corresponds to 1 rad. For this reason, an exposure of 1 R is considered approximately equivalent to an absorbed dose of 1 rad, and the unit "roentgen"is loosely (but incorrectly) used to mean "rad."

To be up to date, an exposure of 1 R is often called a dose of 1 centigray (cGy). The exposure unit bears a simple quantitative relationship to the dosimetric unit (the gray or the rad) that permits the calculation of absorbed dose in any medium whose exposure (in coulombs per kilogram or statcoulombs per cubic centimeter air) is known.

Example 5.5

Consider a γ-ray beam of energy 0.3 MeV. If the photon flux is 10^3 quanta/cm^2/s and the air temperature is 20°C, what is the exposure rate at a point in this beam and what is the absorbed dose rate for soft tissue at this point?

Solution

The linear energy absorption coefficient for air, μ_a, at STP, for 300-keV photons is found to be 3.46×10^{-5} cm^{-1}. The exposure rate, $\dot{X}$, in C/kg/s in a photon flux φ is given by

$$\dot{X} = \frac{\phi \dfrac{\text{photons}}{\text{cm}^2/\text{s}} \times E \dfrac{\text{MeV}}{\text{photon}} \times 1.6 \times 10^{-13} \dfrac{\text{J}}{\text{MeV}} \times \mu_{\text{air}}/\text{ cm}}{\rho_{\text{air}} \dfrac{\text{kg}}{\text{cm}^3} \times 34 \dfrac{\text{J/kg}}{\text{C/kg}}}, \qquad (5\text{-}9)$$

where

μ_a is the linear energy absorption coefficient for air for the photon energy and ρ_a air density . The radiation absorbed dose rate from this exposure is

$$\dot{D} = \frac{\phi \dfrac{\text{photons}}{\text{cm}^2 \cdot \text{s}} \times E \dfrac{\text{MeV}}{\text{photon}} \times 1.6 \times 10^{-13} \dfrac{\text{J}}{\text{MeV}} \times \mu_\text{m}\ \text{cm}^{-1}}{\rho_\text{m} \dfrac{\text{kg}}{\text{cm}^3} \times 1 \dfrac{\text{J/kg}}{\text{Gy}}},$$

where

μ_m is the linear energy absorption coefficient of the medium and
ρ_m is the density of the medium.

Substituting the appropriate numerical values into Eq. (6.9), we have

$$\dot{X} = \frac{10^3 \times 0.3 \times 1.6 \times 10^{-13} \times 3.46 \times 10^{-5}}{(1.293 \times 10^{-6} \times \frac{273}{293}) \times 34}$$

$$\dot{X} = 4 \times 10^{-11} \frac{\text{C/kg}}{\text{s}}.$$

$$4 \times 10^{-11} \frac{\text{C/kg}}{\text{s}} \times 3.6 \times 10^3 \frac{\text{s}}{\text{h}} = 1.5 \times 10^{-7} \frac{\text{C/kg}}{\text{h}}$$

$$= 0.15\ \frac{\mu\text{C/kg}}{\text{h}}.$$

Since $0.258\ \dfrac{\mu\text{C}}{\text{kg}} = 1$ mR, the exposure rate expressed in traditional units is

$$\dot{R} = 0.15\ \frac{\mu\text{C/kg}}{\text{h}} \times \frac{1\ \text{mR}}{0.258\ \dfrac{\mu\text{C}}{\text{kg}}} = 0.58 \frac{\text{mR}}{\text{h}}$$

The absorbed dose rate, in Gy/s, is given by Eq. (5.10) as

$$\dot{D} = \frac{\phi \dfrac{\text{photons}}{\text{cm}^2 \cdot \text{s}} \times E \dfrac{\text{MeV}}{\text{photon}} \times 1.6 \times 10^{-13} \dfrac{\text{J}}{\text{MeV}} \times \mu_{\text{m}}\ \text{cm}^{-1}}{\rho_{\text{m}} \dfrac{\text{kg}}{\text{cm}^3} \times 1 \dfrac{\text{J/kg}}{\text{Gy}}}. \qquad (5.10)$$

The ratio of absorbed dose rate to the exposure dose rate is given by the ratio of Eq. (5.10) to Eq. (5.9):

$$\frac{\dot{D}}{\dot{X}} = \frac{\left(\phi \times E \times 1.6 \times 10^{-13} \times \mu_{\text{med}}\right) / \rho_{\text{med}}}{\left[\dfrac{\left(\phi \times E \times 1.6 \times 10^{-13} \times \mu_{\text{air}}\right)}{\left(\rho_{\text{air}} \times 34 \dfrac{\text{J/kg}}{\text{C/kg}}\right)}\right]}.$$

The absorbed dose rate, in Gy per unit time, resulting from an exposure of $\dot{X}$ C/kg per unit time, therefore is

$$\dot{D},\ \frac{\text{Gy}}{\text{time}} = 34\frac{\text{Gy}}{\frac{\text{C}}{\text{kg}}} \times \frac{\left(\dfrac{\mu_{\text{med}}\ \text{cm}^{-1}}{\rho_{\text{med}}\ \dfrac{\text{g}}{\text{cm}^3}}\right)}{\left(\dfrac{\mu_{\text{air}}\ \text{cm}^{-1}}{\rho_{\text{air}}\ \dfrac{\text{g}}{\text{cm}^3}}\right)} \times \dot{X}\frac{\text{C/kg}}{\text{time}}. \quad (5.10)$$

(5.11)

Since the mass absorption coeff. is given by

$$\mu_{\text{mass}} = \frac{\mu_{\text{linear}}}{\rho},$$

Eq. (5.11) may be written as

$$\dot{D},\ \text{Gy} = 34\frac{\text{Gy}}{\text{C/kg}} \times \left(\frac{\mu_{\text{medium}}}{\mu_{\text{air}}}\right)_{\text{mass}} \times \dot{X}\ \frac{\text{C/kg}}{\text{time}}. \quad (5.12\text{-a})$$

Equation (5.12a) is also applicable to the calculation of the absorbed dose if the exposure dose is used instead of the exposure dose rate. To obtain a dose in rads to any medium when the exposure is given in roentgens, we use the analogous expression

$$\text{rads} = \frac{87.7}{100} \times \left(\frac{\mu_{\text{medium}}}{\mu_{\text{air}}}\right)_{\text{mass}} \times \text{roentgens}. \qquad \textbf{\textit{(5.12b)}}$$

Example 5.6

What is the radiation absorbed dose corresponding to an exposure dose of 25.8 μC/kg (100 mR) from 300-keV photons?

Solution

When the value for the energy absorption coefficient for muscle tissue for 0.3-MeV photons, $\mu_{medium} = 0.0317\ cm^2/g$ and $\mu_{air} = 0.0288\ cm^2/g$, are substituted into Eq. (5.12a), one get;

$$\text{Dose} = 34\frac{\text{Gy}}{\text{C/kg}} \times \frac{0.0317\ \text{cm}^2/\text{g}}{0.0288\ \text{cm}^2/\text{g}} \times 25.8 \times 10^{-6}\ \frac{\text{C}}{\text{kg}} = 9.7 \times 10^{-4}\ \text{Gy}$$

$$= 0.97\ \text{mGy} = 97\ \text{mrads}.$$

Eqs (5.12a) and (5.12b) show that the radiation dose absorbed from any given exposure is determined by the ratio of the mass absorption coefficient of the medium to that of air. In the case of tissue, the ratio of dose to exposure remains approximately constant over the quantum energy range of about 0.1–10 MeV because the chief means of interaction between the tissue and the radiation is Compton scattering, and the cross section for Compton scattering depends mainly on electronic density of the absorbing medium.

In the case of lower energies, photoelectric absorption becomes important, and σ for this mode of interaction increases with Z of the absorber. As a consequence of this dependence on Z , bone, which contains approximately 10% by weight of calcium, absorbs much more energy than soft tissue from a given air dose of low-energy X-rays. This point is illustrated in Fig. 5-6, which shows the number of J/Kg absorbed per C/Kg of exposure for fat, muscle, and bone as a function of quantum energy.

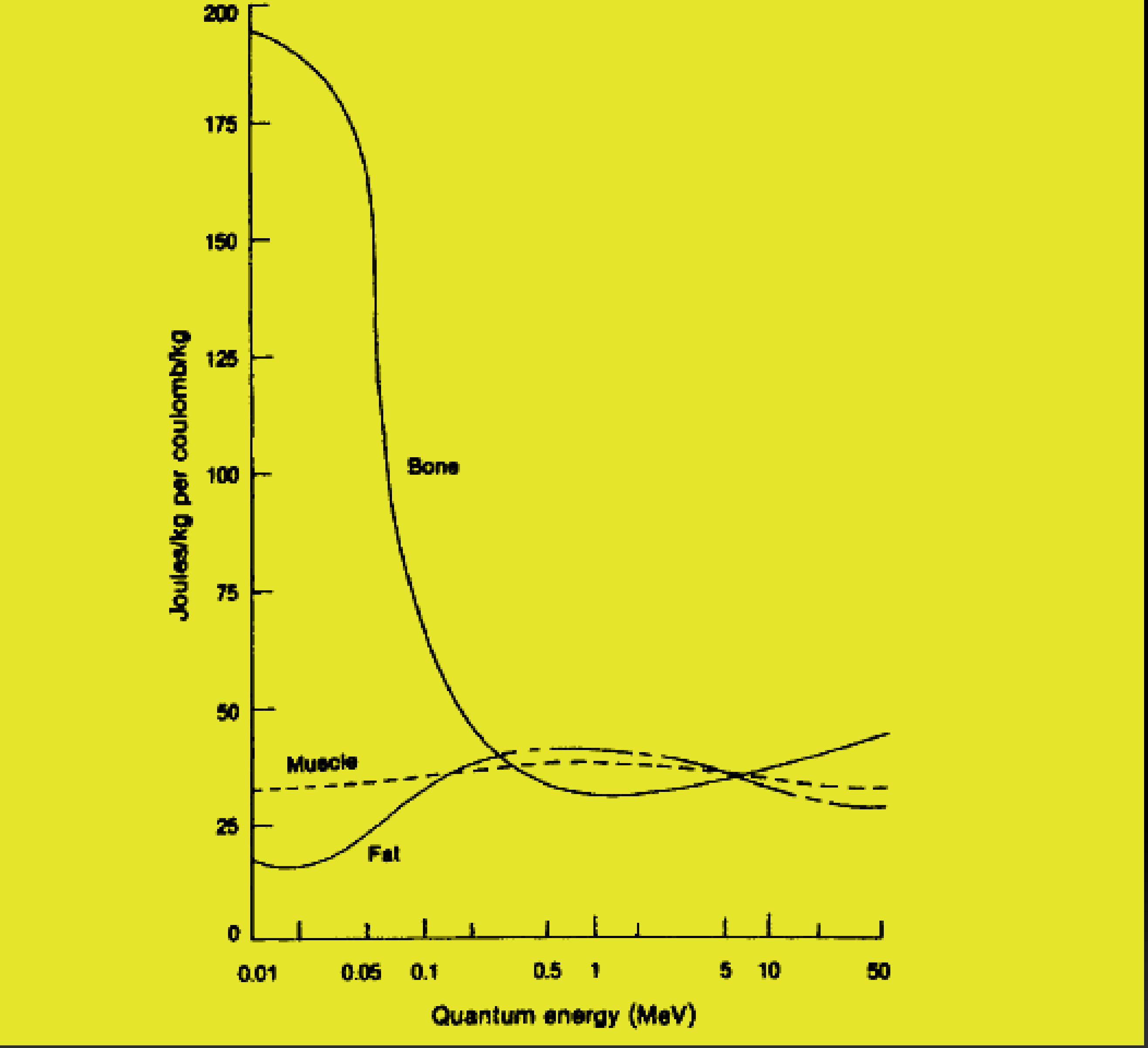


Figure 5-6. Energy absorption per X unit (coulomb per kilogram) exposure for several tissues.

Absorbed Dose Measurement: Bragg–Gray Principle

If a cavity ionization chamber is built with a wall material whose radiation absorption properties are similar to those of tissue, then, by taking advantage of the Bragg–Gray principle, an instrument can be built to measure tissue dose directly. According to the Bragg–Gray principle, the amount of ionization produced in a small gas-filled cavity surrounded by a solid absorbing medium is ∞ to the energy absorbed by the solid.

Implicit in the practical application of this principle is that the gas cavity be small enough relative to the mass of the solid absorber to leave the angular and velocity distributions of the primary electrons unchanged. This requirement is fulfilled if the primary electrons lose only a very small fraction of their energy in traversing the gas-filled cavity. If the cavity is surrounded by a solid medium of proper thickness to establish electronic equilibrium, then the energy absorbed per unit mass of wall, dE_m / dM_m is related to the energy absorbed per unit mass of gas in the cavity, dE_g/dM_g, by

$$\frac{dE_m}{dM_m} = \frac{S_m}{S_g} \times \frac{dE_g}{dM_g}, \qquad (5\text{-}13)$$

where

S_m is the mass stopping power of the wall material and
S_g is the mass stopping power of the gas.

Since the ionization per unit mass of gas is a direct measure of dEg/dMg, Eq. (5.13) can be rewritten as

$$\frac{dE_m}{dM_m} = \rho_m \times w \times J \qquad (5\text{-}14)$$

where

$\rho_m = S_m / S_g$,
w = the mean energy dissipated in the production of an ion pair in the gas, and
J = the number of ion pairs per unit mass of gas.

One can compute ρ_m for electrons of any given energy. For those cases where the gas in the cavity is the same substance as the chamber wall, such as methane and paraffin, ρm is equal to unity. Table 5-1 shows the stopping power ratios, relative to air, of several substances for monoenergetic electrons. For gamma radiation, however, the problem of evaluating ρ_m is more difficult.

The relative fraction of the γ rays that will interact by each of the competing mechanisms, as well as the spectral distribution of the primary es (Compton, photoelectric, and pair-produced electrons) must be considered, and a mean value for relative stopping power must be determined. For the equilibrium electron spectra generated by gamma rays from ^{198}Au, ^{137}Cs, and ^{60}Co, the values for the mean mass relative stopping powers are given in Table 5-2.

TABLE 5-1. Mean S_m Ratios, Relative to Air, for Electronic Equilibrium Spectra Generated by Initially Monoenergetic Electrons

	ELEMENT AND STATE OF MOLECULAR BINDING								
Initial Energy (MeV)	Hydrogen, Saturated	Hydrogen, Unsaturated	Carbon, Saturated	Carbon, Unsaturated	Carbon, highly Chlorinated	Nitrogen, amines, Nitrates	Nitrogen Ring	Oxygen, —O—	Oxygen, O=
0.1	2.52	2.59	1.016	1.021	1.047	0.976	1.018	0.978	0.994
0.2	2.52	2.59	1.015	1.019	1.043	0.978	1.016	0.979	0.995
0.3	2.48	2.55	1.014	1.018	1.040	0.979	1.016	0.981	0.995
0.327	2.48	2.54	1.014	1.018	1.040	0.979	1.015	0.981	0.995
0.4	2.46	2.53	1.014	1.018	1.038	0.980	1.015	0.981	0.996
0.5	2.44	2.51	1.013	1.017	1.037	0.980	1.015	0.982	0.996
0.6	2.44	2.50	1.012	1.016	1.035	0.980	1.013	0.981	0.995
0.654	2.43	2.49	1.011	1.014	1.034	0.979	1.012	0.981	0.994
0.7	2.42	2.48	1.010	1.013	1.033	0.978	1.011	0.980	0.993
0.8	2.40	2.46	1.009	1.012	1.031	0.978	1.010	0.979	0.992
1.0	2.39	2.44	1.004	1.008	1.026	0.975	1.005	0.977	0.988
1.2	2.37	2.42	1.001	1.004	1.022	0.973	1.002	0.974	0.985
1.308	2.36	2.42	0.999	1.002	1.019	0.971	1.000	0.972	0.983
1.5	2.35	2.39	0.995	0.998	1.015	0.967	0.996	0.969	0.980

For air, w, the mean energy loss for the production of an ion pair in air, has a value of 34 eV. To determine the radiation absorbed dose, it is necessary only to measure the ionization J per unit mass of gas.

TABLE 5-2. Mean Mass Stopping Power Ratios, S_m / S_{air} for Equilibrium Electron Spectra Generated by ^{198}Au, ^{137}Cs, and ^{60}Co, on the Assumption That the Electrons Slow Down in a Continuous Manner

	MEDIUM		
ENERGY (MeV)	Graphite	Water	Tissue
0.411 (^{198}Au)	1.032		
0.670 (^{137}Cs)	1.027	1.162	1.145
1.25 (^{60}Co)	1.017	1.155	1.137

Example 5.7

Calculate the absorbed dose rate from the following data on a tissue-equivalent chamber with walls of equilibrium thickness embedded within a phantom and exposed to ^{60}Co gamma rays for 10 minutes. The volume of the air cavity in the chamber is 1 cm3, the capacitance is 5 μF, and the gamma-ray exposure results in a decrease of 72 V across the chamber.

Solution

The charge collected by the chamber is

$$Q = C \times \Delta V$$

$$= 5 \times 10^{-12}\ \mathrm{F} \times 72\ \mathrm{V}$$

$$= 3.6 \times 10^{-10}\ \mathrm{C}.$$

The number of electrons collected, which corresponds to the number of ion pairs formed in the air cavity, is

$$\frac{3.6 \times 10^{-10}\ \mathrm{C}}{1.6 \times 10^{-19} \frac{\mathrm{C}}{\text{electron}}} = 2.25 \times 10^{9}\ \text{electrons.}$$

Since 34 eV are expended per ion pair formed in air and since the stopping power of tissue relative to air is 1.137 (Table 5-2), we have from the Bragg–Gray relationship of Eq.(5.14):

$$\frac{\mathrm{d}E_m}{\mathrm{d}M_m} = \rho_m \times w \times J$$

$$= \frac{1.137 \times 34 \frac{\text{eV}}{\text{ip}} \times 2.25 \times 10^{9} \frac{\text{ip}}{\text{cm}^3} \times 1.6 \times 10^{-19} \frac{\text{J}}{\text{eV}}}{1.293 \times 10^{-6} \frac{\text{kg}}{\text{cm}^3} \times 1 \frac{\text{J/kg}}{\text{Gy}}}$$

$$= 0.0108\ \text{Gy} = 10.8\ \text{mGy}\ (1.08\ \text{rad} = 1080\ \text{mrad}).$$

The exposure time was 10 minutes and the dose rate therefore is 1.08 mGy/min (108 mrad/min).

Kerma

In the case of indirectly ionizing radiation, such as X-rays, γ rays, and fast neutrons, we are sometimes interested in the initial kinetic energy of the primary ionizing particles (the photoelectrons, Compton electrons, or positron–negatron pairs in the case of photon radiation and the scattered nuclei in the case of fast neutrons) that result from the interaction of the incident radiation with a unit mass of interacting medium.

This quantity of transferred energy is called the kerma, K, and is measured in SI units in joules per kilogram, or grays. In the traditional system of units, it is measured in ergs per gram or in rads. Although kerma and dose are both measured in the same units, they are different quantities. The kerma is a measure of all the energy transferred from the uncharged particle (photon or neutron) to primary ionizing particles per unit mass, whereas absorbed dose is a measure of the energy absorbed per unit mass.

Not all the energy transferred to the primary ionizing particles in a given volume of material may be absorbed in that volume. Some of this energy may leave that volume and be absorbed elsewhere. This could result from bremsstrahlung or annihilation radiation which is generated by the primary ionizing particles, but which leave the volume element without further interactions within that volume. It may also be the result of failure to attain electronic equilibrium within the volume element underconsideration.

In a large medium, where electronic equilibrium exists and where we have insignificant energy loss by bremsstrahlung, kerma is equal to absorbed dose The difference between kerma and dose is illustrated by Example 5.8.

Example 5.8

A 10-MeV photon penetrates into a 100-g mass and undergoes a single interaction ,a pair-production interaction that leads to a e^+ and an e^- of 4.5 MeV each. Both charged particles dissipate all their kinetic energy within the mass through ionization and bremsstrahlung production. Three bremsstrahlung photons of 1.6,1.4, and 2MeVeach that are produced escape from the mass before they interact. The positron, after expending all its kinetic energy, interacts with an ambient electron within the mass and they mutually annihilate one another to produce two photons of 0.51 MeV each, and both these photons escape before they can interact within the mass. Calculate

(a) the kerma and

(b) the absorbed dose.

Solution

(a) Kerma is defined as the sum of the initial kinetic energies per unit mass of all charged particles produced by the radiation. In this case, a positron–negatron pair of 4.5 MeV each (2 × 4.5 MeV) represents all the initial kinetic energy. The kerma, K, in this case is

$$K = \frac{\text{kinetic energy released}}{\text{mass}} = \frac{2 \times 4.5\ \text{MeV} \times 1.6 \times 10^{-13}\ \dfrac{\text{J}}{\text{MeV}}}{0.1\ \text{kg} \times 1\ \dfrac{\text{J/kg}}{\text{Gy}}}$$

$$= 1.44 \times 10^{-11}\,\text{Gy}.$$

(b) Dose is defined as the energy absorbed per unit mass. Here we have the 9 MeV of initial kinetic energy, of which (1.6 + 1.4 + 2) MeV was converted into bremsstrahlung and into 2 photons of 0.51-MeV annihilation radiation. All these photons escaped from the 100-g mass. The absorbed dose, therefore, is

$$D = \frac{\text{absorbed energy}}{\text{mass}}$$

$$= \frac{[10\ \text{MeV} - (1.6 + 1.4 + 2 + 2 \times 0.51)\ \text{MeV}] \times 1.6 \times 10^{-13} \dfrac{\text{J}}{\text{MeV}}}{0.1\ \text{kg} \times 1 \dfrac{\text{J/kg}}{\text{Gy}}}$$

$$= 6.4 \times 10^{-12}\ \text{Gy}.$$

The National Council on Radiation Protection and Measurements (NCRP) specifies X-ray machine output and X-ray levels in units of air kerma. Since electronic equilibrium generally is attained in an X-ray field in air, air kerma is, for practical purposes, a measure of exposure. The numerical relationship between air kerma and exposure in C/kg and in R is :

$$1\ \mathrm{C/kg} = 34\ \mathrm{Gy}\ (\text{in air})$$

$$1\ \mathrm{Gy}\ (\text{air kerma}) = \frac{1}{34}\frac{\mathrm{C}}{\mathrm{kg}} = 0.02941\frac{\mathrm{C}}{\mathrm{kg}}$$

$$1\ \mathrm{mGy}\ (\text{air kerma}) = 0.02941 \times 10^{-3}\frac{\mathrm{C}}{\mathrm{kg}} = 2.94 \times 10^{-5}\frac{\mathrm{C}}{\mathrm{kg}} = 29.4\ \frac{\mu\mathrm{C}}{\mathrm{kg}}.$$

In traditional units, exposure measured in R that corresponds to 1 Gy air kerma is

$$1\ \mathrm{Gy}\ (\text{air kerma}) = 0.02941\frac{\mathrm{C}}{\mathrm{kg}} \times 3881\ \frac{\mathrm{R}}{\mathrm{C/kg}} = 114\ \mathrm{R}$$

$$1\ \mathrm{mGy}\ (\text{air kerma}) = 114\,\mathrm{mR}.$$

Example 6.9

The NCRP recommends 0.1mGyair kerma in 1 week as the shielding design criterion for limiting occupational exposure to medical X-rays. What is the corresponding weekly exposure limit in units of (a) mR? (b)μC/kg?

Solution

(a) $0.1 \text{ mGy air kerma} \times 114 \dfrac{\text{mR}}{\text{mGy}} = 11.4 \text{ mR in 1 week.}$

(b) $0.1 \text{ mGy air kerma} \times 29.4 \dfrac{\mu\text{C/kg}}{\text{mGy}} \text{ air kerma} = 2.94 \dfrac{\mu\text{C}}{\text{kg}}$ in 1 week.

Kerma decreases continuously with increasing depth in an absorbing medium because of the continuous decrease in the flux of the indirectly ionizing radiation . The absorbed dose, however, is initially less at the surface of an absorbing medium than below the surface. It increases as electronic equilibrium is approached and the ionization density increases due to the increasing number of secondary ions produced by the primary ionizing particles (the positron–electron pairs,

Compton electrons, and photoelectrons in the case of photon beams and scattered nuclei in the case of fast neutrons). This increase in absorbed dose continues until a maximum is reached, after which the absorbed dose decreases with continuing increase in depth. The maximum absorbed dose occurs at a depth approximately equal to the maximum range of the primary ionizing particles. The relation between kerma and dose for photon radiation and for fast neutrons is shown in Figure 5-7.e

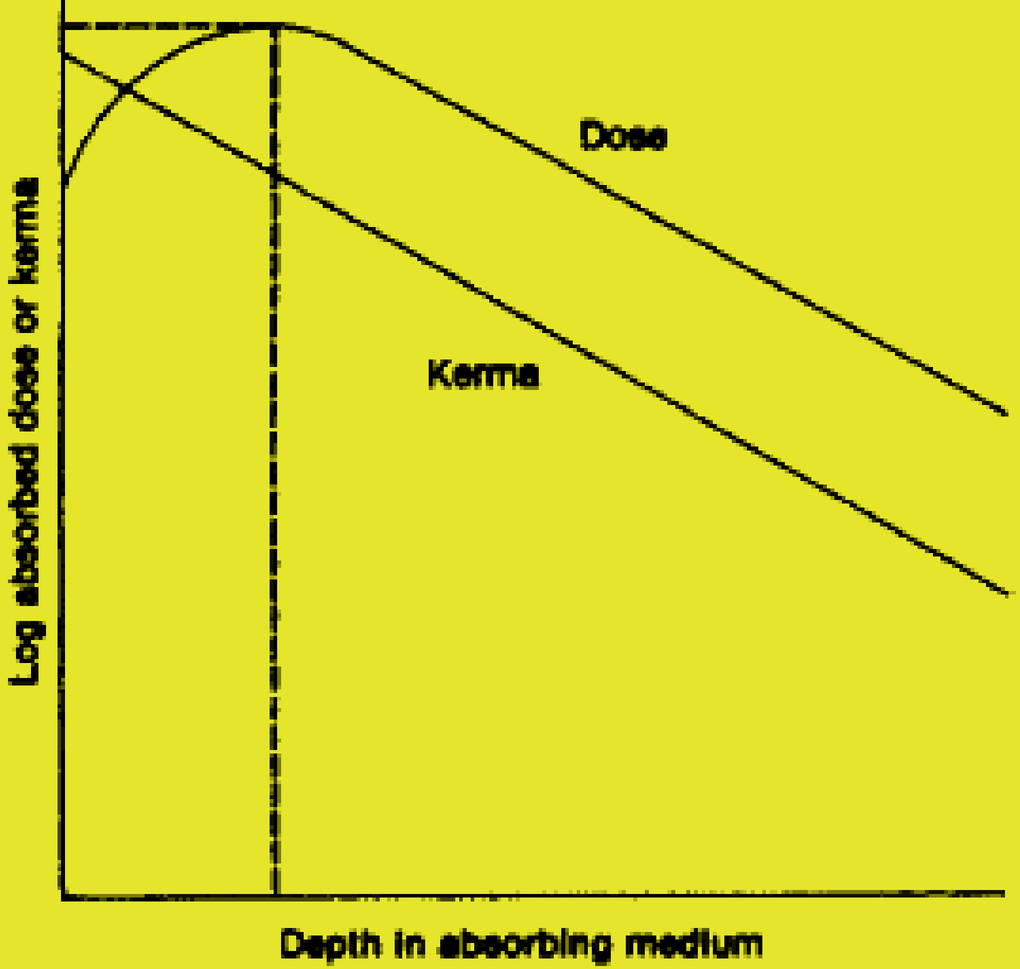


Fig 5-7. Relation between kerma and absorbed dose for photon radiation and for fast neutrons